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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 4 : G06F 15/72, 15/66, 15/20 G09G 15/14

A1

(11) International Publication Number: WO 86/ 07646

(43) International Publication Date: 31 December 1986 (31.12.86)

(21) International Application Number: PCT/US86/01356

(22) International Filing Date: 19 June 1986 (19.06.86)

(31) Priority Application Number: 746,626

(32) Priority Date: 19 June 1985 (19.06.85)

(33) Priority Country: US

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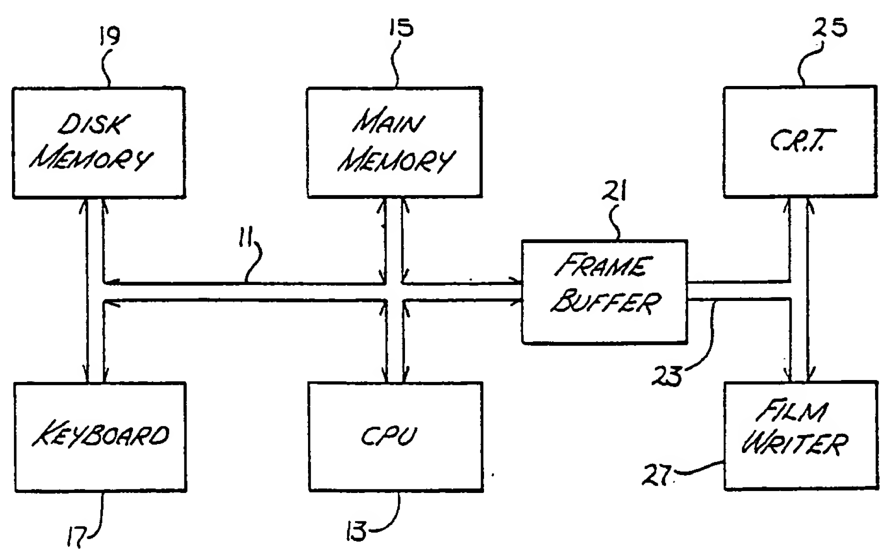
(81) Designated States: AT, AT (European patent), AU, BB, BE (European patent), BG, BR, CH, CH (European patent), DE, DE (European patent), DK, FI, FR (European patent), GB, GB (European patent), HU, IT (European patent), JP, KP, KR, LK, LU, LU (European patent), MC, MG, MW, NL, NL (European patent), NO, RO, SD, SE, SE (European patent), SU.

Published
With international search report.

(54) Title: PSEUDO-RANDOM POINT SAMPLING TECHNIQUES IN COMPUTER GRAPHICS



(57) Abstract

A computer database contains visual and other information of an object scene from which a television monitor (25) or film display (27), is created by electronically sampling points of the object scene information in the computer memory (15, 19). Undesirable effects of aliasing are significantly reduced and substantially eliminated by pseudo-randomly distributing, in a particular manner, the occurrence of the point samples in space and time. Realistic depth of field is obtained in the images, corresponding to what is observed through a camera lens, by altering the sample point locations to simulate passing them through an optical aperture (93) in a pseudo-random distribution thereacross. Further, effects of illumination, shadows, object reflection and object refraction are made more realistic by causing each sample point to pseudo-randomly select one of a predetermined number of possible ray directions.

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PSEUDO-RANDOM POINT SAMPLING TECHNIQUES IN COMPUTER GRAPHICS

Background of the Invention

This invention relates generally to the art of computer graphics, and more specifically to the field of point sampling of visual scene information for the purpose of reconstructing an image of the visual scene.

One form of computer graphics that is becoming widely practiced is to develop the sequence of video image frames of a moving object scene from information of the scene that has been stored in a computer memory. The object scene database contains information of the visual characteristics of the object scene, such as color, as well as information of movement. The creator of a sequence of video frames then uses a computer to electronically assemble signals of each video frame from the database in a manner that provides the views and movement of the object scene that is desired by the operator to be displayed.

The electronic signal for each video frame is typically developed by electronic sampling of the object scene database. A separate set of digital signals is developed to represent the color and/or intensity of each pixel of a standard raster scanned video monitor, for each video frame produced. Each pixel is thus the smallest

resolution element of the video display. The color and/or intensity of each pixel is determined by sampling the database information to determine the characteristics of the object scene at the location of a given pixel. Such sampling is generally done by averaging the object scene information over a certain portion of the area of the pixel, or, more commonly, to sample the information at one or more points within the pixel, usually in some form of a periodically repeating pattern.

Recent developments in the field of computer graphics have been directed to increasing the realism of the resulting images. Progress has been made in more faithfully reproducing object textures, shadows, reflections and transparencies, for example. Much effort has been directed to the problem of aliasing, as well. Existing sampling techniques tend to generate video image frames having "alias" images; that is, images that appear to be real but which are not specified in the computer database. This is generally recognized as a characteristic of images formed through variously used point sampling techniques.

Therefore, it is a general object of the present invention to provide computer graphics techniques that further improve the realism of the resulting video image frames and the totality of video productions generated from computer database representations of an object scene.

Summary of the Invention

This and additional objects are accomplished by the present invention wherein, briefly and generally, the object scene information in the computer database is sampled by points that are pseudo-randomly distributed in

one or several functions or dimensions. According to one aspect of the invention, the point samples are pseudo-randomly distributed in a particular manner across the video image plane being constructed. According to another aspect, the pseudo-random distribution of point samples is taken over the time that is occupied by the video image frame being constructed. This substantially reduces or eliminates the undesirable aliasing, both spatially and temporally. The distribution of samples over time also increases the realism of the video frame by adding the image blurring that would occur if the object scene was being photographed according to usual techniques.

According to another aspect of the present invention, a video frame is constructed to have a depth of field by sampling the data base as if the object scene represented by it is being viewed through a lens of a limited aperture that will view in focus only a limited depth of the object scene. The point samples are pseudo-randomly directed over a defined lens aperture when sampling the database information.

According to another specific aspect of the present invention, reflective and transparent characteristics of an object are taken into account by recognizing the degree of diffusion that occurs at each sample point. A particular angle of reflection or refraction is pseudo-randomly selected for each sample point from a range of possible angles depending upon the object characteristics. This adds realism to the resultant image by recognizing the diffuse, blurry nature of reflections and translucency that is possessed by most real objects.

According to yet another aspect of the present

invention, an intensity distribution is specified for a light source that is illuminating the object scene. A single light source ray is pseudo-randomly selected from the specified light source distribution, for each sample point. This technique has the advantage of eliminating harsh shadows that result from existing techniques, further adding to the improved realism of the images, when a light source is only partially obscured.

Additional objects, advantages and features of the various aspects of the present invention will become apparent from the description of its preferred embodiments, which description should be taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

Figure 1 illustrates generally a computer system that is suitable for carrying out the various aspects of the present invention;

Figure 2 illustrates one possible form of object scene information that is stored in the computer memories of Figure 1;

Figures 3 and 4 illustrate two existing point sampling techniques;

Figures 5, 6 and 7 show three specific embodiments of the pseudo-random spatial techniques of the present invention;

Figure 8 illustrates spatial aliasing of the prior art techniques of Figures 3 and 4;

Figure 9 illustrates the improvement brought about by the pseudo-random point sampling techniques of the present invention;

Figure 10 shows a Fourier transform of a periodically sampled signal;

Figure 11 shows a Fourier transform of a pseudo-randomly sampled signal;

Figure 12 illustrates generally the distribution of the point samples over time;

Figures 13, 14, 15 and 16 illustrate several specific embodiments of the pseudo-random time sampling aspect of the present invention;

Figure 17 illustrates generally computer database sampling by a given distribution of sample points on an image plane;

Figure 18 shows a sampling technique that provides an image with a depth of field;

Figure 19 is a ray tracing example for a single sample that includes the effects of reflection, refraction and light source distribution;

Figures 20, 21 and 22 illustrate additional details of the example shown in Figure 19; and

Figure 23 provides yet another application of the general techniques of the present invention.

Description of the Preferred Embodiments

Referring initially to Figure 1, a general computer system as illustrated that is suitable for carrying out the various aspects of the present invention to be described in detail below. A common bus 11 is connected to a central processing unit (CPU) 13 and main memory 15. Also connected to the bus 11 is keyboard 17 and a large amount of disk memory 19. Either a commercially available VAX-11/780 or Cray large computer system is satisfactory. A frame buffer 21 receives output information from the bus 11 and applies it, through another bus 23, to a standard color television monitor 25 or another peripheral 27 that writes the resulting image

frames directly onto film, or both. Additionally, an output device can simply be a videotape recorder of the standard type.

Figure 2 illustrates the organization of the information of the object scene that is maintained in memory in the computer system of Figure 1. There are many ways to store such information, one being selected for illustration in connection with the present invention. This technique involves breaking down the object scene into components, these elements being referred to herein as geometric primitives. One such geometric primitive is a polygon 31, for example, illustrated in Figure 2 within an overlay 33 that shows in dotted outline a few adjacent pixels of the resulting display. The resulting display, of course, shows the color and intensity of the object scene within each pixel to be uniform, the size of the pixel being the resolution element size of display. The polygon represents portions of the object scene to be represented in a video frame.

The information stored in the computer memory for each object polygon is as extensive as necessary for producing a particular quality video image frame. Its position certainly must be a piece of that information, conveniently specified by the x, y and z coordinates. The x, y and z coordinates of each of the corner points of the polygon are stored for each video frame to be constructed, as shown in Figure 2 with respect to the polygon 31. The "x" and "y" numbers represent, of course, the horizontal and vertical positions, respectively, of the points, while the "z" number specifies its distance behind the video frame (image plane) being constructed.

In order to be able to sample movement of the

object scene that occurs in the time period of one image frame, a technique described in detail below, information is also maintained for each polygon of its movement during such time period. In Figure 2, a second position 31' of the same polygon is illustrated with its corner point coordinates being stored as incremental changes over that of their initial positions. The position shown for the polygon 31 is preferably, for example, that at the beginning of a video frame, while the position 31' is that at the end of the video frame. The polygon can also change its shape during this time period.

Besides the positions of each object surface polygon being stored in the data base, certain visual characteristics are stored for each, as well. These include separate red, green and blue color reflection signals, red, green and blue transparency signals, extent of light diffusion upon reflection, extent of light dispersion upon transmission through the surface, and similar characteristics. The use of these and others are explained below in connection with the techniques of the present invention.

Referring to Figure 3, a commonly used technique for determining the color and/or intensity of each pixel of the image frame is illustrated. The information in the computer database, in this example that of the polygons illustrated in Figure 2, that is present in the space occupied by a particular pixel is determined for a plurality of points within the pixel. A large number of points are illustrated in Figure 3, being periodically distributed in both dimensions, but there are even some techniques that use only one or a very few sample points per pixel. The nature of the object scene in each such sample point is determined, and those

determinations are combined in some manner, such as by weighted or unweighted averaging, in order to determine the color and intensity of that pixel of the image frame.

Figure 4 illustrates a similar periodic point sampling technique, except that not all point samples are taken in each case. Rather, the full density of the periodic sampling pattern is employed only in regions of a pixel where changes in the object scene occur, such as represented by a line 35. This image dependent technique thus reduces the number of samples and the processing time required.

But these and other periodic sampling techniques result in reconstructed images that include "aliases" of the real image to be displayed. Much effort has been directed to anti-aliasing techniques, one approach being to process the video signal obtained from a periodic pattern point sample technique in order to eliminate the aliasing effects of the technique. Others have suggested sampling in a non-periodic, dithered manner for a number of specific sampling applications. The techniques of the present invention include improvements to and new applications of such prior approaches.

Three different specific pseudo-random sampling techniques are illustrated in Figures 5, 6 and 7, wherein a single pixel is illustrated and, for simplicity of illustration, only four point samples per pixel are described. However, an actual implementation would likely use sixteen, or even as many as sixty-four samples per pixel, if all of the aspects of the present invention are utilized. For other specific implementations, a lesser number of samples, such as one per pixel, could be utilized. But in any event, the pattern of point

samples, both within each pixel and across the face of the image frame in its entirety, are non-periodic, and form a non-rectangular and non-rectilinear grid pattern. Further, each selected sampling pattern may, alternatively, extend over an area of multiple pixels or only part of a pixel. But the examples described herein use a sampling area coincident to that of one pixel, for simplicity of explanation.

Each of the embodiments of Figures 5, 6 and 7 determines the location of the sample points within the pixel by first dividing the pixel into a number of non-overlapping areas equal to the number of sample points, in this case four. A sample point is confined within each such area, thus aiding in keeping the sample points spread out. The four areas of the pixel are labeled in the Figures as numbers 41, 43, 45 and 47. The areas are shown to be rectangular but can be some other shape.

In the embodiment of Figure 5, the location of the sample point for each of these four areas is pseudo-randomly determined. Ideally, the "random" numbers to be used to determine their locations are purely randomly, but since they are so determined by computer, there is some element of repetitiveness of sample position within its defined area, although the distribution of locations of a large number of sample locations matches that of a random distribution. The most common way for a computer to generate the x,y coordinates of each sample point is to use a look-up table maintained in memory that has a list of numbers with a distribution being that of a random set of numbers. But the usual technique is for the computer to step through the table of numbers in sequence, so there are some repetitions since the table of numbers has finite length. However, the length of the list of numbers can be

quite large so that repetition does not occur for a significant number of sample points. But in order to adequately describe both a completely random selection of sample locations and one controlled by such a computer look-up table, the locations are referred to here in this description as "pseudo-random".

In an implementation of the technique of Figure 5, the same sample pattern is used on every pixel in a given image frame. It is preferable, however, to eliminate all periodicity of the sample pattern, including making sure that no two adjacent pixels have the same sample pattern. This can be done by using a sufficiently long look-up table of random numbers. It is preferable to generate a sample pattern with no two adjacent pixels (including those diagonally adjacent) having the same pattern, a result of the techniques shown in Figures 6 and 7.

Referring to Figure 6, each of the four non-overlapping areas of the pixel illustrated has a reference point positioned at a fixed location in each, such as its middle. Each actual sample point location is then determined by the computer by adding a random positive or negative number to each of the reference point's x and y coordinates. These offset numbers are randomly determined, such as from the computer random number look-up table, and so repetition of the pattern would not occur for some very large number of pixels.

Another application of the same offset technique is a combination of the techniques of Figures 5 and 6, as shown in Figure 7. This is similar to that of Figure 5 and differs from that of Figure 6 by having its reference points distributed rather than fixed in the middle of the adjacent pixel areas. The reference point

pattern of the embodiment of Figure 7 may be the same for each pixel, but the actual point sample locations are determined by adding a positive or negative x,y coordinate offset increment to the coordinates of each reference point. For convenience, a limit is placed on the maximum offset of each, as indicated by the dotted outline around each of the reference points of Figure 7. The sample points in the embodiment of Figure 6, however, can be located anywhere within its respective portion of the area of the pixel.

By first defining non-overlapping areas in which a single sample point lies, bunching up of sample points is avoided. It can be visualized that if each of the four sample points could be positioned anywhere within the entire pixel, there would be occasions, because of the random selection of those specific locations, where two or more of the sample points would be bunched together. Although defining a range of potential point sample locations to be within a non-overlapping area accomplishes this, there could obviously be some variations of this specific technique, such as by allowing the areas to overlap slightly, or some other variation. It may even cause no problem in particular applications if the sample points are chosen in a manner that their bunching together does occur occasionally.

Each of the specific techniques described with respect to Figures 5, 6 and 7 provides a picture sampled from a computer database that has fewer aliased images than if a periodic point sample distribution is utilized. The technique shown in Figure 5, wherein the same pattern is repeated for each pixel of the image framē, provides some improvement, but the techniques according to Figures 6 and 7 are significantly better in reducing aliasing.

The technique of Figure 7 has been observed to be the best of the three because it has an additional advantage of being less noisy.

Referring to Figure 8, an example of how an aliased image can be obtained and displayed is given. Figure 8(A) is a "picket fence" image of "slats" 51, 53, 55, 57 and 59. This image is being sampled by a periodic distribution of points 61, 63, 65, 67 and 69, shown only in a single dimension for simplicity. Since the period of the sample points is greater than that of a periodic intensity variation of the image, all of those variations will not be faithfully reproduced. Figure 8(B) shows the image of a video display that is developed from the samples of Figure 8(A), region 71 being of one intensity and region 73 being of the other. Of course, the image of Figure 8(B) is not a faithful reproduction of the image of Figure 8(A). But since three of the sample points hit a portion of the image having one intensity and the other two a portion of the image having the other intensity, the detail of the other variations cannot be faithfully reproduced. The curve of Figure 8(C) represents the intensity variation of the image of Figure 8(A), the curve of Figure 8(D) being the sampling function, and the curve of Figure 8(E) illustrating the resulting image of Figure 8(B).

One way that has been suggested to avoid forming such alias images is to increase the number of sample points so that the detail can be captured. That is to say, increase the number of samples in order to increase the well-known Nyquist limit. But to use extra sample points for this increases the computational complexity and can never really solve the problem; it only reduces its appearance somewhat. No matter how many

samples are used, however, there will always be some situations of aliasing, particularly when the scene is changing. In this case, such a picket fence can show as a flashing black-and-white image over a large area, a very undesirable result.

Referring to Figure 9, the effect of a randomly distributed pattern of sample points is illustrated. Figure 9(A) assumes the same "picket fence" image in the computer database, as with Figure 8(A). But the sample points in Figure 9(A) are distributed non-periodically so that the resulting image of Figure 9(B) appears to be gray rather than having large areas that are all white or all black. The image of Figure 9(B) appears gray since alternate portions of the image are black-and-white, rather than having large areas of each color as in Figure 8(B). Further, as the point samples of Figure 9(A) are scanned relative to the "picket fence" image, there will be some noisy visual effect, similar to film grain noise, but one of considerably less annoyance than a large area flashing black or white. The noise level is controlled by the number of samples per unit area.

Figures 10 and 11 show in the frequency domain the effect of periodic and stochastic point sampling, respectively. In both of Figures 10 and 11, curves (A) are the same, being an original signal, chosen to be a sine wave in the space domain. Curves (B) differ, however, in that Figure 10(B) shows the frequency distribution of a spatially periodic sampling pattern, while Figure 11(B) shows the frequency distribution of the ideal stochastic sampling pattern. In both cases, the sampling frequency is assumed to be below the Nyquist limit of the original signal, so will not be able to faithfully reproduce the original signal. But the

comparison of the curves of Figures 10 and 11 show the anti-aliasing effect of a random distribution. The spatial sampling distribution across the image is preferably chosen so that a Fourier transform of such a distribution over an infinite plane approximates a Poisson disk distribution, as shown in Figure 11(B). The primary characteristics of such a distribution include a very high level at zero frequency, a substantially zero magnitude to a certain frequency (both positive and negative), and then a substantially constant magnitude at higher frequencies. Except at zero frequency, the sampling function in the frequency domain (Figure 11(B)) is substantially continuous. Such a distribution in the frequency domain provides the desired spatial position randomness and avoids bunching of the sample points. The techniques described with respect to Figures 5-7 approximate such a distribution.

The distribution (C) in each of Figures 10 and 11 shows the sampled signal in each of those examples, the result of convolving the signal of curve (A) with the sampling distribution of curve (B). In the periodic spatial sample example of Figure 10, a number of extraneous spikes are obtained since each of the sampling spikes of Figure 10(B) is individually convolved with each of the spikes of the signal of Figure 10(A). Since the frequencies of the signal of Figure 10(A) are in excess of that of the sampling function of Figure 10(B), the sampled signal of Figure 10(C) is not a faithful reproduction of that of the original signal. When the sampled signal of Figure 10(C) is displayed, it is in effect multiplied by a lowpass filter similar to that of of Figure 10(D). The resultant sampled signal is shown in Figure 10(E), which is the portion of the signal of

Figure 10(C) which is within the band pass of the filter function of Figure 10(D). The signal indicated at Figure 10(E) is capable of reconstructing alias images that bear little or no resemblance to that of the original signal which was sampled.

The sampled signal of Figure 11(C) also does not correspond with the original signal of Figure 11(E), but when multiplied by its filter characteristics of Figure 11(D), the resultant sampled signal of Figure 11(E) is uniform over the frequency range of the filter. This produces in an image white noise, which is much preferable to reconstructing an apparent genuine image that does not exist.

The techniques described with respect to Figures 5-7 can also be utilized in a sampling system that modifies the sampling pattern in response to the content of the image information being sampled, so called adaptive sampling. For example, if image changes or detail within a portion of a sampling area required it, the pattern of sample points can be repeated in such an area portion in reduced scale.

According to another aspect of the present invention, similar sampling techniques are employed over time in order to add realistic motion blur, such as exist in video and film techniques. Referring initially to Figure 12, the example pixel of Figures 5-7 is indicated to have each of its four samples taken at different times t1, t2, t3 and t4, regardless of the specific technique used to spatially locate the point samples. These times are selected to be within an interval that corresponds to a typical shutter opening for video frame acquisition which these techniques are intended to simulate. Therefore, if there is movement of the objects during the

interval of a single frame indicated in the computer database, then the resultant image of that frame reconstructed from the samples being taken of the database information will similarly show motion blur.

In order to reduce or substantially eliminate temporal aliasing, the distribution in time of the samples over the frame interval is pseudo-randomly determined. Referring to Figure 13, a time line is given wherein four non-overlapping intervals of time are designated as boundaries for each of the four sample points to occur. A pseudo-random selection of the time for each sample within each of these intervals is what is shown in Figure 13. The same time distribution in Figure 13 could be used for each pixel of the image frame being constructed, but is preferable that the sample times be different for at least each of immediately adjacent pixels, in order to maximize the anti-aliasing that is desired. Temporal aliasing can occur when changes occur in the scene, such as a flashing light, more rapidly than samples are being taken. It will also be recognized that the distribution in time illustrated in Figure 13 involves the same considerations as the spatial distribution described with respect to Figure 5.

Similarly, Figures 14 and 15 illustrate psuedo-random temporal sampling that is carried out in the same way as the spatial sampling described with respect to Figures 6 and 7, respectively. In Figure 14, the time of each sample is chosen to be a pseudo-randomly determined offset from the center of the interval designated for each sample to occur. In Figure 15, a reference time is pseudo-randomly determined for each sample within its interval, and then the actual time for each sample is determined as a shift from this reference an amount that

least one sample point in a substantially different relative position within the boundaries of its pixel from that of all other neighboring pixels.

11. The method according to claim 8 wherein said improvement additionally comprises locating a plurality of sample points within each pixel and wherein said computer data base contains information of spatial movement of the objects during a time period represented by said image frame, and further wherein the color and/or intensity of the objects is determined for each of the plurality of sample points within each pixel at one of a plurality of different instants during said image frame time period, thereby to show any motion blur of the object scene in the resulting image frame electronic signal.

12. The method according to claim 8 wherein said improvement additionally comprises the steps of establishing the characteristics of an optical imaging system, including aperture size and focal plane relative to the objects of the scene, and determining the characteristics of the objects for each sample by taking into account the distance of the objects from the focal plane and the size of the lens aperture, whereby the image frame electronic signal contains information of the objects with a certain depth of field as determined by the characteristics of the optical imaging system.

13. The method according to claim 8 wherein said improvement additionally comprises the steps of determining, for the sample points individually, a range of angles of reflection and/or refraction of the object scene at such points, and pseudo-randomly selecting one

5. The improved method according to claim 1 wherein said at least one stored parameter includes a range of angles of reflection from objects in the scene.

6. The improved method according to claim 1 wherein said at least one stored parameter includes a range of angles of refraction by objects in the scene.

7. The improved method according to claim 1 wherein said at least one stored parameter includes a range of spatial intensity variations of illumination of objects in the scene.

8. In a method of forming an electronic signal of a video image frame that individually specifies the color and/or intensity of each of an array of pixels that forms said frame, wherein the color and/or intensity of each pixel is determined by sampling, at at least one point within a boundary of each of said pixels, data stored in a computer data base that specifies spatial locations and visual characteristics of objects in a scene for said image frame, the improvement comprising electronically positioning said sample points in a spatial distribution across said frame such that a Fourier transform of such a distribution over an infinite plane is substantially continuous in some regions.

9. The improved method according to claim 8 wherein the grid pattern includes a plurality of sample points in substantially all of the pixels of the frame.

10. The method according to claim 8 wherein the improvement additionally comprises locating said at

IT IS CLAIMED:

1. In a method of forming an electronic signal of a video image frame that individually specifies the color and/or intensity of each of an array of pixels that forms said frame, wherein the color and/or intensity of each pixel is determined by point sampling, at at least one point within a boundary of each of said pixels, data stored in a computer data base that specifies various parameters relating to an object scene, the improvement wherein the sampling is electronically accomplished by a pseudo-random distribution of at least one of said stored parameters such that a Fourier transform of such a distribution over an infinite extent contains substantially continuous regions.

2. The improved method according to claim 1 wherein said at least one stored parameters includes location of objects in the scene relative to the image frame.

3. The improved method according to claim 1 wherein said at least one stored parameter includes an amount that the objects in the scene change during the time represented by said video image frame, whereby object blur of said object scene is represented.

4. The improved method according to claim 1 wherein said at least one stored parameter includes a range of ray paths representative of that created by an optical imaging system, whereby a depth of field of said object scene is represented.

sampling of Figures 14 and 15 herein, depth of field of figure 18 herein, and secondary rays of Figures 19-22 for shadowing and reflection in a special image case. The resultant images of Figures 3, 5 and 7 of the above-referenced published paper, were made on a Cray computer with the source code listing of Appendix A.

Appendix B is a program that implements all of the aspects of the present invention for spherical objects and resulted in the images of Figures 4, 6 and 8 of the above-referenced published paper.

These computer programs contain material in which a claim of copyright is made by Lucasfilm, Ltd., the assignee hereof. This assignee has no objection to the duplication of Appendices A and B by photocopying and the like but reserves all other copyright rights therein.

Although the various aspects of the present invention have been described with respect to various preferred embodiments thereof, it will be understood that the invention is entitled to protection within the full scope of the appended claims.

the broad extent of the techniques described above that are a part of the present invention. The techniques can be used to determine a center of mass of an object, an example of something that is desirable to be determined in the course of computer aided design (CAD). An object 141 of Figure 23 has its surfaces determined by a pseudo-random distribution of sample points, shown to extend through the object in dotted outline. The pseudo-random nature of this sampling assures that the measurement will be made on the actual object 141 and not some alias image of it.

The various techniques of the present invention have also been described by the inventors in a published paper, "Distributed Ray Tracing", Computer Graphics, Vol. 18, No. 3, pages 137-145, July, 1984, which is incorporated herein by reference. This paper includes photographs of images generated with the use of the various aspects of the present invention. The result of motion blur, as described with respect to Figures 12-16, is shown in Figures 3, 6 and 8 of that paper. Computer generated images having a depth of field are shown in Figures 4 and 5 of that paper, having been made by the techniques described with respect to Figure 18 herein. Figure 7 of that paper illustrates the shadowing and reflection techniques of the present invention that were described with respect to Figures 19-22 above.

Appendices A and B attached hereto are source code listings, in the C language, of computer programs implementing the various aspects of the invention described herein. They are part of a hidden surface algorithm. Appendix A is a general program that carries out the spatial sampling techniques of Figures 6 and 7 herein, one of which is optionally selected, temporal

the possible refractive angles, another portion 125 of the object scene can then be determined which is intersected by the ray 121 and is partially visible through the object portion 113.

In order to avoid sharp shadows, the realistic characteristics of an object scene illuminating light source 127 is taken into account. As shown in Figures 19 and 22, the light source 127 has a finite extended dimension, and is not always a point as often assumed in present computer graphics techniques. A ray 129 is traced from the illuminated surface 113 back to the source 127 to see if there is any other portion of the object scene, such as the portion 131, that will cause a shadow to be cast on the surface 113. As shown in the example of Figure 19, the ray 129 will detect no such shadow, but other possible ray directions, as shown in Figure 22, will be in the path of the object portion 131 and thus indicate that the object 113 is not illuminated by the source 127. The particular direction of the ray 129 is pseudo-randomly selected from those possible directions specified for the source 127, as shown in dotted outline in Figure 22. In the example of Figure 19, some of the rays will intersect the object portion 131 and some will not, resulting in soft, realistic shadows in the resulting image frame.

It will be recognized that each of the secondary surfaces intersected by rays, such as the surfaces 117 and 125 of Figure 19, may also have reflective and translucent properties. The process is continued until such reflected or transparent images are so small in intensity as not to make any difference in the resulting image being constructed.

Referring to Figure 23, an example is given of

The object surface portion 117 may be observed in the completed image frame as a reflection in the object scene portion 113. But stored in the computer database is a diffusive light spread of the surface 113, as indicated by dotted outline 119 and shown separately in Figure 20. If the characteristics of the surface 113 are specularly reflecting, such as occurs with a mirror, the spread of possible ray reflection angles will be limited to essentially one. But most objects have some degree of diffusion and will scatter light incident upon them. Therefore, each sample point ray is traced in a manner to select one of the possible reflection angles, thereby to result in a realistic blurry reflection from diffusely reflecting surfaces since subsequent rays will be reflected off the surface 113 at one of the other possible angles shown in Figure 20. The possible ray reflection angles, as shown in Figures 19 and 20, are weighted in one direction, as is actually the case in diffusely reflecting surfaces. And, as before, the particular direction taken by any given ray 115 is pseudo-randomly selected from the possible reflection angles.

The same consideration works in determining an angle of transmission of a ray 121 through the surface portion 113 if that surface portion is at all translucent. Assuming that it is, possible angles of refraction are stored in the computer database for that particular polygon, the distribution of such angles being indicated at 123 in Figure 19 and also shown in Figure 21. The spread of possible refractive angles depends, of course, on how diffuse the translucency is. Plain glass, for example, will have a very narrow range of refractive angles, if not a single angle. And once the ray 121 is pseudo-randomly selected for a given sample point from

95 and 97 shown in Figure 18, are pseudo-randomly determined in the same manner as the earlier described pseudo-random determination of the spatial location and time of each sample point.

Other unrealistic effects that result from the use of existing computer graphics techniques are sharp shadows, glossy reflections, and, if translucency of objects is taken into account at all, that also results in sharp images showing the translucent objects. This, of course, is not the real world of diffuse objects and extended light sources, but are required simplifying assumptions under previous algorithms in order to maintain within reason the complexity of the calculations. But the distributed techniques of the present invention can also be applied to these tasks, in a similar manner as described previously, to add these realistic considerations. Referring to Figure 19, a single ray 111 is traced from a single sample on the image plane (not shown) and interacts with the object scene in a manner specified by the characteristics of the light sources and object surfaces that are specified in the database. The techniques described with respect to Figure 19 are independent of the techniques described earlier, but, of course, maximum realism is obtained if all of these techniques are combined together. What is to be described with respect to Figure 19 occurs with each sample point of a particular image frame.

The ray 111 is first determined to strike a surface 113 of the object scene, as specified by one of the polygons whose characteristics are stored in the computer database. If this part of the object scene surface is reflective, a reflective ray 115 is then traced until it intersects another object scene surface 117.

frames.

The example rays 89 and 91 of Figure 18 do not extend directly behind the image plane, as was described with respect to Figure 17, but rather are directed to intersect a simulated lens 93 at points 95 and 97, respectively. These rays then are directed again toward each other, under influence of refraction of the simulated lens. The rays intersect a focal plane 99 of the simulated optical system in the same pattern as exists on the image plane, as a result of defining the simulated optical system. The sample point rays 89 and 91 will then intersect polygons 101 and 103, respectively. Only polygons within the cone 105, shown in dotted outline, will be intersected with rays from sample points of the pixel 87, as defined by the characteristics of the optical system. Those polygons that are close to the focal plane 99 will contribute to a focused reconstructed image, while those further removed from the focal plane 99 contribute to an unfocused reconstructed image. In a computer software implementation of this technique, it has been found preferable to shift the x,y coordinates of the polygons an amount dependent upon their z distance from the focal plane 99 and the characteristics of the simulated optical system, and then proceed with the sampling in a manner similar to that shown in Figure 17.

But whatever specific implementation is carried out, the technique has the advantage of adding considerable realism to the simulated image at the time that the image is first formed by sampling the database. Intersection of sample rays with the simulated lens 99 occurs over its entire defined aperture. In order to further reduce aliasing, the location of points of intersection of the rays with the lens, such as the points

location of these point samples has been determined by one of the techniques described above. Their individual rays are then projected, usually perpendicularly to the image plane, to determine the nearestmost polygons that are intersected by the rays at their selected time of sample. Much work has been done on such ray tracing techniques and involves a significant computer sort and matching of the x,y coordinates of the sample points with those of the polygons in the computer database at the instant designated for the taking of each sample. Usually, more than one polygon will exist at each x,y sample location, so the computer also determines from the "z" information of them which is the closest to the image plane, and that is then the one that provides the visual information (color, etc.) of the object scene at that point. All of the visual characteristics determined for each of the samples of a given pixel are then averaged in some manner to form a single visual characteristic for that pixel for display during that frame.

Most computer graphics techniques show the entire object scene for each frame in focus, as if it was being viewed through a pinhole camera. This, of course, is not an accurate simulation of the real world of cameras and lenses, which have a limited depth of field. Depth of field can be taken into account by a ray tracing technique illustrated in Figure 18. A single pixel 87 has two sample points with rays 89 and 91 extending from them behind the image plane. The depth of field technique illustrated in Figure 18 is independent of the spatial and temporal sampling techniques described above, but it is preferable that those techniques be used in combination with the depth of field techniques being described in order to maximize the realism of the resulting image

performance of the following steps electronically:

spatially dividing the area of said pixel into a plurality of non-overlapping areas,

determining a nominal point location within each of said areas in a non-regular pattern,

pseudo-randomly determining an offset of each such nominal point within each of said areas for each pixel within said image frame,

determining from the computer data base the color and/or intensity of the closest of said objects at each offset point for each pixel of said frame, and

combining the color and/or intensity information of the samples in each pixel, thereby to determine a single color and/or intensity of each pixel.

29. In a method of forming an image frame by individually controlling the color and/or intensity of each pixel in an array of pixels that forms said frame, wherein objects to be included in said image frame are represented by data stored in a computer data base that specifies spatial locations and visual characteristics of said objects for said image frame, a method of accessing the information of the computer data base for determining the color and/or intensity of each pixel, comprising performing the following steps electronically:

spatially dividing the area of said pixel into a plurality of non-overlapping areas,

determining a nominal point location in substantially the center of each of said areas,

pseudo-randomly determining an offset of each nominal point within each of said areas for each pixel within said image frame,

determining from the computer data base the

27. In a method of forming an image frame by individually controlling the color and/or intensity of each pixel in an array of pixels that forms said frame, wherein objects to be included in said image frame are represented by data stored in a computer data base that specifies spatial locations and visual characteristics of said objects for said image frame, a method of accessing the information of the computer data base for determining the color and/or intensity of each pixel, comprising performance of the following steps electronically:

spatially dividing the area of said pixel into a plurality of non-overlapping areas,

pseudo-randomly positioning a sample point within substantially each of said areas, thereby to determine the position of a plurality of sample points for each pixel,

determining from the computer data base the color and/or intensity of the closest of said objects at each of the plurality of sample points for each pixel of said frame, and

combining the color and/or intensity information of the samples in each pixel, thereby to determine a single color and/or intensity of each pixel.

28. In a method of forming an image frame by individually controlling the color and/or intensity of each pixel in an array of pixels that forms said frame, wherein objects to be included in said image frame are represented by data stored in a computer data base that specifies spatial locations and visual characteristics of said objects for said image frame, a method of accessing the information of the computer data base for determining the color and/or intensity of each pixel, comprising

said improvement additionally comprises the steps of determining, for said sample points individually, a range of angles of reflection and/or refraction of the object scene at each point, and pseudo-randomly selecting one such angle for each such sample point, whereby other portions of the object scene that are visible by reflection from or transparency through a sampled point of the object scene are determined.

25. The method according to claim 17 wherein said improvement additionally comprises the steps of determining, for the sample points individually, a range of angles of rays extending from each such point to a source of illumination of the scene, pseudo-randomly selecting one such ray angle for each such point, and determining for each of said selected rays whether other objects are in the path of the ray, whereby penumbras are shown in the image frame.

26. In a method of forming an electronic signal of a video image frame that individually specifies the color and/or intensity of each of an array of adjacent areas that forms said frame, wherein the color and/or intensity of each such area is determined by sampling, at a plurality of points in a certain pattern within a boundary of substantially every such area across said image frame, data stored in a computer data base that specifies spatial locations and visual characteristics of an object scene for said image frame, the improvement comprising the steps of electronically defining a plurality of substantially non-overlapping portions within such area and then locating each sample point within an individual area portion.

20. The method according to claim 17, wherein said electronic information contains information of spatial movement of the object scene during a time period represented by said image frame, and further wherein the color and/or intensity of the object is determined for each of the plurality of sample points within each frame area at one of a plurality of different instants during said image frame time period, thereby to show any motion blur of the object scene that occurs during the time period of said image frame.

21. The method according to claim 20, wherein said one of a plurality of different instants of time is pseudo-randomly determined for said sample points.

22. The method according to claim 17 wherein said improvement additionally comprises the steps of establishing the characteristics of an optical imaging system, including aperture size and focal plane relative to the objects of the scene, and determining the characteristics of tne objects for each sample by taking into account the distance of the objects from the focal plane and the size of the lens aperture, whereby the image frame electronic signal contains information of the objects with a certain depth of field as determined by the characteristics of the optical imaging system.

23. The method according to claim 22 wherein the step of determining the characteristics of the objects includes pseudo-randomly distributing the path of sample points through said lens aperture.

24. The method according to claim 17 wherein

such angle for each such sample point, whereby other portions of the object scene that are visible by reflection from or transparency through a sampled point of the object scene are determined.

14. The method according to claim 8 wherein said improvement additionally comprises the steps of determining, for the sample points individually, a range of angles of rays extending from each such point to a source of illumination of the scene, pseudo-randomly selecting one such ray angle for each such point, and determining for each of said selected rays whether other objects are in the path of the ray, whereby penumbras are shown in the image frame.

15. In a method of forming an electronic signal of a video image frame that individually specifies the color and/or intensity of each of an array of adjacent areas that forms said frame, wherein the color and/or intensity of each such area is determined by sampling, at a plurality of points in a certain pattern within a boundary of substantially every such area in said image frame, data stored in a computer data base that specifies spatial locations and visual characteristics of an object scene for said image frame, the improvement comprising electronically arranging said plurality of sample points in a manner that said certain pattern of substantially every such area is different than said certain pattern of substantially all other of such areas that are immediately adjacent thereto.

16. The method according to claim 15 wherein said improvement includes making substantially all of

such areas coincident with pixels of the resulting video image frame.

17. In a method of forming an electronic signal of a video image frame that individually specifies the color and/or intensity of each of an array of adjacent areas that forms said frame, wherein the color and/or intensity of each such area is determined by sampling, at a plurality of points in a certain pattern within a boundary of substantially every such area across said image frame, data stored in a computer data base that specifies spatial locations and visual characteristics of an object scene for said image frame, the improvement comprising electronically arranging said plurality of sample points within substantially every such area in a spatial distribution therein such that a Fourier transform of such a distribution over an infinite plane is substantially continuous in some regions.

18. The method according to claim 17 wherein said improvement additionally comprises the step of causing said certain pattern of sample points within substantially every one area to be different from that of substantially all its immediately adjacent areas.

19. The method according to claim 17 wherein said improvement additionally comprises determining the certain pattern of sample points for each such area by a method comprising the steps of defining a plurality of substantially non-overlapping portions within such area and then locating each sample point within an individual area portion.

source of illumination of the scene, pseudo-randomly selecting one such ray angle for each such point, and determining for each of said selected rays whether other objects are in the path of the ray, whereby penumbras are shown in the image frame.

48. In a method of forming an electronic signal of a video image frame that individually specifies the color and/or intensity of each of an array of pixels that forms said frame, wherein the color and/or intensity of each pixel is determined by sampling, at a plurality of points within a boundary of each of said pixels, data stored in a computer data base that specifies visual characteristics of an object scene for said image frame, the improvement comprising the steps of electronically determining, for the sample points individually, a range of angles of rays extending from each such point to a source of illumination of the scene, pseudo-randomly selecting one such angle for each such point, and determining for each of said selected rays whether other objects are in its path, whereby penumbras are shown in the image frame.

49. A system for developing an electronic signal and displaying an image of an object scene therefrom, comprising:

a computer memory database that specifies certain static and time varying visual characteristics of the object scene,

means responsive to said computer memory for sampling information of the database to determine the visual characteristics of the object scene at a plurality of points pseudo-randomly positioned across the object

sampled point of the object scene are determined.

45. The method according to either of claims 42 or 43, wherein said improvement additionally comprises the steps of determining, for the sample points individually, a range of angles of rays extending from each such point to a source of illumination of the scene, pseudo-randomly selecting one such ray angle for each such point, and determining for each of said selected rays whether other objects are in the path of the ray, whereby penumbras are shown in the image frame.

46. In a method of forming an electronic signal of a video image frame that individually specifies the color and/or intensity of each of an array of pixels that forms said frame, wherein the color and/or intensity of each pixel is determined by sampling, at a plurality of points within a boundary of each of said pixels, data stored in a computer data base that specifies visual characteristics of an object scene for said image frame, the improvement comprising the steps of electronically determining, for the sample points individually, a range of angles of reflection and/or refraction of the object scene at such points, and pseudo-randomly selecting one such angle for each such sample point, whereby other portions of the object scene that are visible by reflection from or transparency through a sampled point of the object scene are determined.

47. The method according to claim 46 wherein said improvement additionally comprises the steps of determining, for the sample points individually, a range of angles of rays extending from each such point to a

the color and/or intensity of each of an array of pixels that forms said frame, wherein the color and/or intensity of each pixel is determined by sampling, at a plurality of points within a boundary of each of said pixels, data stored in a computer data base that specifies visual characteristics of an object scene for said image frame, the improvement comprising the steps of establishing the characteristics of an optical imaging system, including aperture size and focal plane relative to the objects of the scene, and electronically determining the visual characteristics of the object scene at each point sample by taking into account the distance of the objects from the focal plane and the size of the lens aperture, whereby the image frame electronic signal contains information of the objects with a certain depth of field as determined by the characteristics of the optical imaging system.

43. The improved method according to claim 42 wherein the step of determining the visual characteristics of the object scene for each point sample includes pseudo-randomly determining the point on the lens from which the object scene is sampled within a field of view of the object scene that is determined by the lens aperture and location of the focal plane.

44. The method according to either of claims 42 or 43, wherein said improvement additionally comprises the steps of determining, for the sample points individually, a range of angles of reflection and/or refraction of the object scene at such points, and pseudo-randomly selecting one such angle for each such sample point, whereby other portions of the object scene that are visible by reflection from or transparency through a

comprises the steps of establishing the characteristics of an optical imaging system, including aperture size and focal plane relative to the objects of the scene, and determining the characteristics of the objects for each sample by taking into account the distance of the objects from the focal plane and the size of the lens aperture, whereby the image frame electronic signal contains information of the objects with a certain depth of field as determined by the characteristics of the optical imaging system.

40. The method according to any of claims 34-36, inclusive, wherein said improvement additionally comprises the steps of determining, for the sample points individually, a range of angles of reflection and/or refraction of the object scene at such points, and pseudo-randomly selecting one such angle for each such sample point, whereby other portions of the object scene that are visible by reflection from or transparency through a sampled point of the object scene are determined.

41. The method according to any of claims 34-36, inclusive, wherein said improvement additionally comprises the steps of determining, for the sample points individually, a range of angles of rays extending from each such point to a source of illumination of the scene, pseudo-randomly selecting one such ray angle for each such point, and determining for each of said selected rays whether other objects are in the path of the ray, whereby penumbras are shown in the image frame.

42. In a method of forming an electronic signal of a video image frame that individually specifies

instants during said time period, whereby any motion blur of the object scene is included in the resulting image frame electronic signal.

35. The improved method according to claim 34 wherein the step of sampling the data base at said plurality of points includes doing so pseudo-randomly as a function of time for each such pixel and within said time period of said image frame, whereby the image frame signal has reduced aliasing in time.

36. The improved method according to claim 34 wherein the step of sampling the data base at said plurality of points includes the steps of defining an interval of time for taking a sample for each of said plurality of points for said pixel, and pseudo-randomly determining the instant of each such sample within its said defined interval of time, whereby the image frame signal has reduced aliasing in time.

37. The improved method according to claim 36 wherein the intervals of time defined for taking each sample are substantially non-overlapping.

38. The improved method according to claim 36 wherein the intervals of time defined for taking each sample are overlapped in a manner to increase the concentration of samples in the middle of the intervals of time relative to the concentration at their beginning and end.

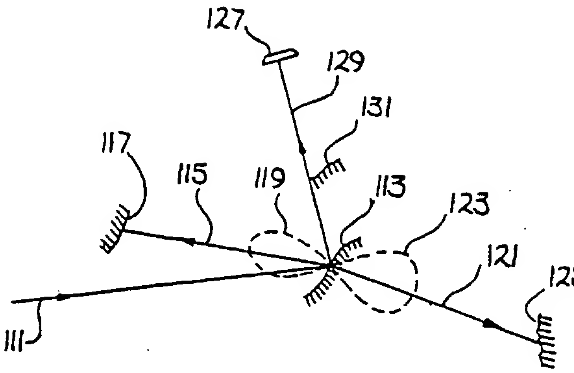
39. The method according to any of claims 34-36, inclusive, wherein said improvement additionally

29, inclusive, wherein said determining step includes a method comprising the steps of determining, for said sample points individually, a range of angles of reflection and/or refraction of the object scene at each point, and pseudo-randomly selecting one such angle for each such sample point, whereby other portions of the object scene that are visible by reflection from or transparency through a sampled point of the object scene are determined.

33. The method according to any of claims 27-29 wherein said improvement additionally comprises the steps of determining, for the sample points individually, a range of angles of rays extending from each such point to a source of illumination of the scene, pseudo-randomly selecting one such ray angle for each such point, and determining for each of said selected rays whether other objects are in the path of the ray, whereby penumbras are shown in the image frame.

34. In a method of forming an electronic signal of a video image frame that individually specifies the color and/or intensity of each of an array of pixels that forms said frame, wherein the color and/or intensity of each pixel is determined by sampling, at a plurality of points within a boundary of each of said pixels, data stored in a computer data base that specifies visual characteristics of an object scene for said image frame, the improvement comprising the steps of including in said computer data base information of changes in the object scene visual characteristics that occur during the time period of said image frame, and electronically sampling the data base at said plurality of points at different

Fig.19



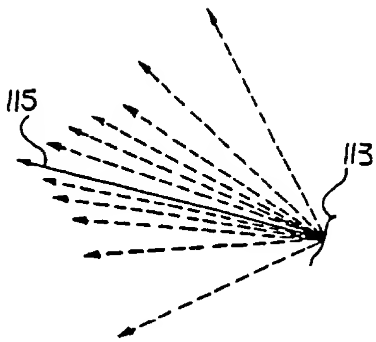


Fig. 20

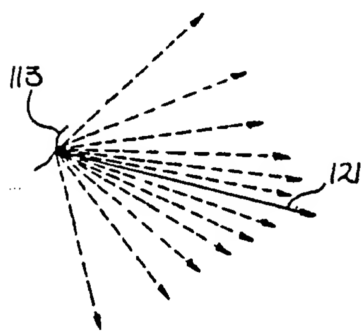


Fig.21

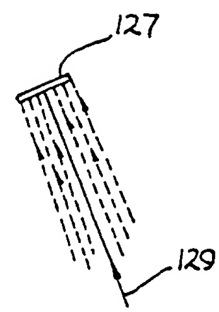


Fig. 22

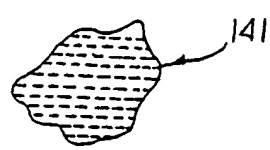


Fig. 23

INTERNATIONAL SEARCH REPORT

International Application No PCT/US86/01356

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC (4): G06F 15/72, 15/66, 15/20; G09G 1/14
U.S. Cl: 364/522, 518, 521; 340/729

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
U.S.	340/725, 729, 747 364/518, 521, 522

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
A	US, A, T912.012 (APPEL ET AL) 24 July 1973	1-52
A	US, A, 3,441,789 (HARRISON III) 29 April 1969	1-52
A	US, A, 4,475,104 (SHEN) 02 October 1984	1-52
A	"Shaded Computer Graphics in the Entertainment Industry" by Crow: Tutorial: Computer Graphics by Booth, spring 1979, pages 382-393	1-52
A	"A Procedure for Generation of Three-dimensional Half-toned Computer Graphics Presentations" by Bouknight and "Models of Light Reflection for computer Synthesized Pictures" by Blinn; Tutorial selected readings in INteractive Computer Graphics by Freeman, spring 1980, pages 292-301 and 316-322.	1-52

* Special categories of cited documents: [15]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
06 August 1986	02 SEP 1986
International Searching Authority [1]	Signature of Authorized Officer [10]
ISA/US	Edward R. Cosimano

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

A	"Rural scene perspective transformation" by Devich et al; Proceedings of SPIE- The International Society for Optical Engineering vol. 303 Visual Simulation and Image Realism II, August 1981 pages 54-66.	1-52
A	"A Lens and Aperture Camera Model for Synthetic Image Generation" by Potmesil et al; Computer Graphics vol. 15, #3 August 1981: pages 297-305.	1-52
A	"Spectral Consequences of Photoreceptor Sampling in the Rhesus Retina" by Yellott, Jr.; Science, vol. 221 22 July 1983: pages 382-385.	1-52

V.☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE [10]

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1.☐ Claim numbers ...., because they relate to subject matter [12] not required to be searched by this Authority, namely:

2.☐ Claim numbers ...., because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out [13], specifically:

VI.☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING [11]

This International Searching Authority found multiple inventions in this international application as follows:

1.☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.

2.☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

3.☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

4.☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

☐ The additional search fees were accompanied by applicant's protest.

☐ No protest accompanied the payment of additional search fees.

International Application No. PCT/US86/01356

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No [18]
A	"Reduction of Display Artifacts by Random Sampling" by Ahumada, Jr. et al; Proceedings of SPIE- The International Society for Optical Engineering vol. 432 Applications of Digital Image Processing VI, August 1983: pages 216-221.	1-52
A	"Distributed Ray Tracing" by Cook et al; Computer Graphics, vol. 18, #3 July 1984: pages 137-145.	1-52
A	"The New Realism" by West; Science84, July/August 1984.	1-52